High accuracy mobile robot positioning using external Large Volume Metrology instruments

Z. Wang, M. Liang and P.G. Maropoulos
Department of Mechanical Engineering, University of Bath, Bath, UK

Abstract

A method of accurately controlling the position of a mobile robot using an external Large Volume Metrology (LVM) instrument is presented in this paper. Utilizing a LVM instrument such as a laser tracker or indoor GPS (iGPS) in mobile robot navigation, many of the most difficult problems in mobile robot navigation can be simplified or avoided. Using the real-time position information from the laser tracker, a very simple navigation algorithm, and a low cost robot, 5mm repeatability was achieved over a volume of 30m radius. A surface digitization scan of a wind turbine blade section was also demonstrated, illustrating possible applications of the method for manufacturing processes. Further, iGPS guidance of a small KUKA omni-directional robot has been demonstrated, and a full scale prototype system is being developed in cooperation with KUKA Robotics UK.

Keywords

Automated Guided Vehicle, AGV, Metrology, Laser Tracker, iGPS

1. Introduction

One of the most difficult problems in mobile robot navigation is the accurate estimation of the robot's position and orientation. A large variety of mobile robot navigation methods ranging from dead reckoning using odometry or inertial navigation systems, to the more complex multi-sensor map-based systems have been developed by a number of research groups (Eric Krotkov et al 1995, Guilherme N et al 2002, Jonathan Dixon and Oliver Henlich 1997, Kok Seng CHONG and Lindsay KLEEMAN 1997). However, most of the proposed methods are not accurate or reliable enough to be used to guide robots in manufacturing processes such as assembly, machining, or inspection. Many of the navigation methods also require significant computing power, which is usually at a premium on small low power mobile robots.

The Large Volume Metrology Group at the University of Bath have developed a proof of concept automated mobile robot surface form inspection system, using a Laser Tracker as both the measurement instrument and robot position feedback. A demonstration of the system's capability, a section of a wind turbine blade was scanned and digitized, the result of which is presented in this paper.

2. System Description

The overall control loop of the system is shown in (Figure 1).

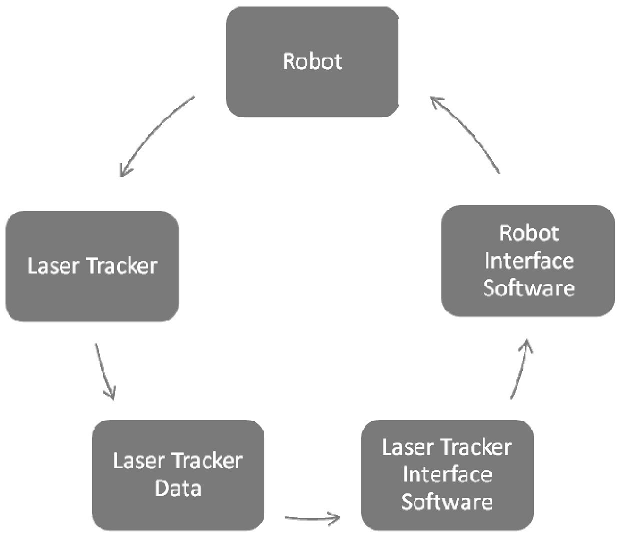

Figure 1 – System overview

The robot's position is recorded using an external Large Volume Metrology (LVM) instrument such as a laser tracker, which sends the position to a instrument interface software on a PC which then passes the information to the robot control software that uses the current robot position and the desired position to compute the speed and steering correction commands.

The commands are sent to the robot wirelessly. Details of the software and control method are discussed in sections 2.3 and 2.4.

2.1. Laser Tracker

The Laser Tracker utilises interferometry for measuring length and a pair of high resolution angle encoders to measure the horizontal and vertical angles of the laser beam. (Figure 2) shows a schematic of the internal components of a typical laser tracker. In the interferometry technique a coherent laser beam of known wavelength passes through a beam-splitter. One beam is reflected back within the system while the other is aimed at a Spherical Mirror Reflector (SMR) that is a sphere with an embedded corner cubed reflector. When the two beams combine, constructive and destructive interference at the laser wavelength can be observed by the detector. The number of the bright and dark patterns is counted by the relevant electronics to calculate the distance. The SMR is used as the instrument probe, thus the laser tracker is a contact measurement system.

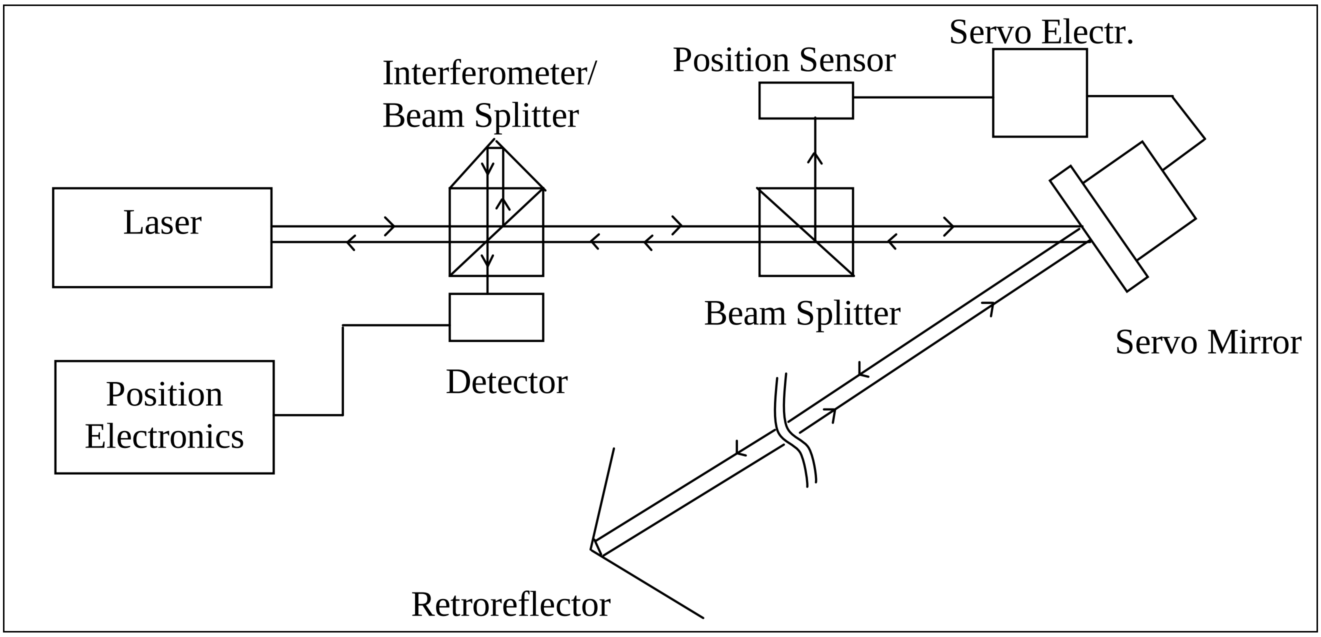

Figure 2 – Interferometry in Laser Trackers (Estler WT et al, 2002).

Laser trackers are considered to be one of the most reliable and well established metrology systems. An international standard exists for the system's performance evaluation (ASME B89.4.19, 2006). Their main drawback is that the line of sight between the laser tracker head and the SMR must be maintained at all times, and only one SMR at any time can be tracked. Some laser trackers provide an Absolute Distance Measurement (ADM) system, which modulates the laser beam and detects the phase of the returned light (Estler WT et al, 2002). By gradually reducing the modulation frequency, the absolute distance of the target can be determined with a high degree of accuracy. ADM enabled laser trackers are more user friendly, since when the line of sight is broken, the tracker can reconnect with the SMR without homing the SMR to the tracker's initial position, as is required for an interferometer system. The ease of use however, comes at the cost of a slight decrease in accuracy (FARO EUROPE GmbH & Co. KG, 2004).

The FARO Tracker SI using in this experiment has a single point angular accuracy (2 sigma) of 18µm + 3µm/m, and distance accuracy (2 sigma) of 20µm + 1.1µm/m in ADM mode, it has a range of 35m. (FARO EUROPE GmbH & Co. KG, 2004)

2.2. Indoor GPS

Typically, the system components of iGPS are (see Figure 3):

- At least two transmitters
- A control centre
- Wired/wireless sensors

Transmitters operate as reference points (with known position) continually generating three signals: two infrared laser fanned beams rotating in the head of the transmitter and an infrared (IR) LED strobe. Sensors are passive elements, which can be placed on the surface of the object to be measured to receive the transmitters' signals. Before starting measurements, the locations of transmitters are solved by measuring a number of points inside the working volume, and applying scaling information between the points.

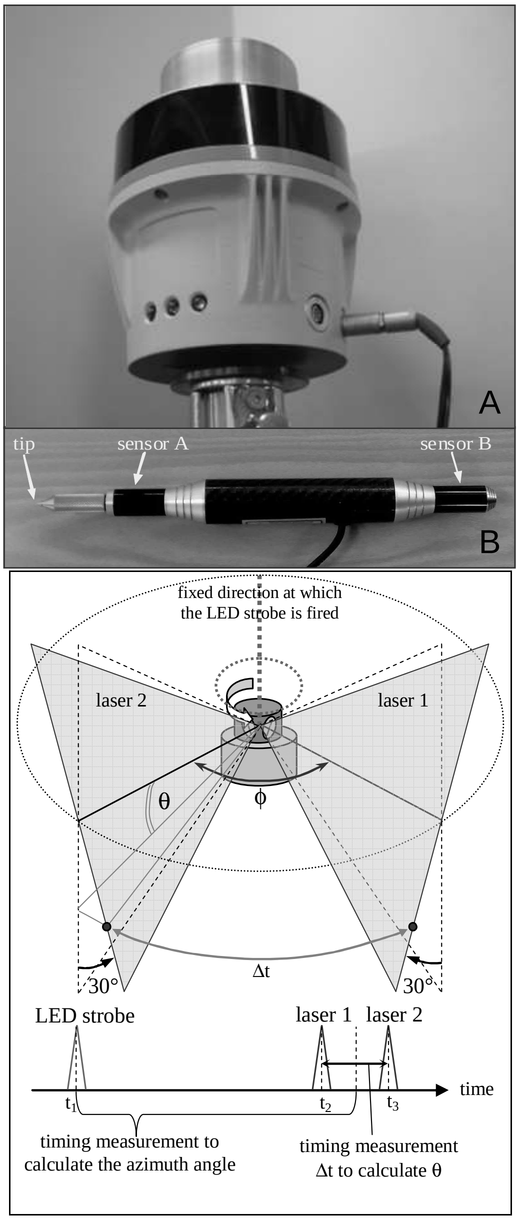

Figure 3 – Top: A) iGPS transmitter. B) Two sensor vector bar. Bottom: Transmitter laser fans and timing diagram of the signal received by the sensor (Z. Wang et al, 2002)

During measurements, the position (x, y, and z) of each sensor is calculated. Each transmitter-sensor pair acts in the same way as a Theodolite-target pair, producing two angular measurements: the horizontal (azimuth) and the vertical (elevation) angles. Sensors can triangulate their position whenever they are located in the line-of-sight of two or more transmitters (ARCSecond, 2002).

The technique used by each transmitter-receiver pair to determine the azimuth and elevation angles is as follows (ARCSecond, 2002). Each transmitter generates two rotating infrared laser beams and an infrared LED strobe. These optical signals are converted into timing pulses through the use of a photo detector. The rotation speed of the spinning head in each transmitter is set to a different value in order to differentiate between the transmitters. Additionally, the transmitter angular velocity is continuously tracked and used to convert the timing intervals into angles. As shown in the Figure 3 (bottom), the two fanned beams, radiated from the rotating head of each transmitter, are tilted with respect to the rotation axis, nominally at -30° and +30°.

The measurement of azimuth angle requires a horizontal index, which is created by firing an omni-directional LED strobe at a fixed direction in the rotation of the transmitter's head.

2.3. Mobile Robot

The mobile robot, shown in (Figure 4) and (Figure 5) used in this proof of concept experiment is a low cost LEGO MINDSTORM NXT system, with a 32bit processor, USB and Bluetooth support.

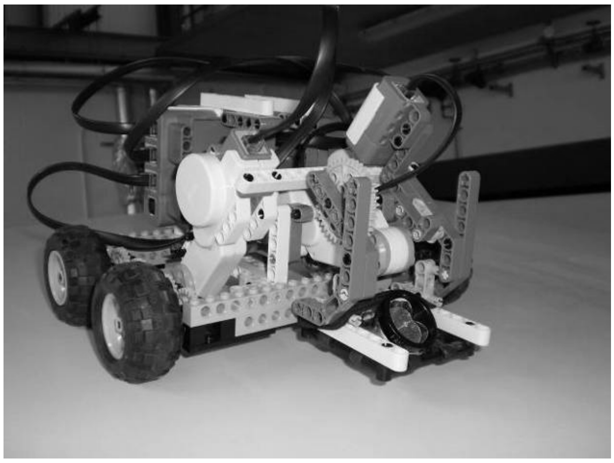

Figure 4 – Mobile robot carrying a laser tracker SMR

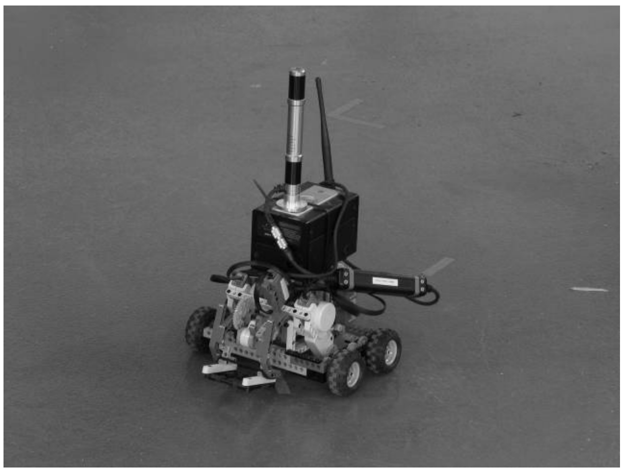

Figure 5 - Mobile robot carrying an iGPS vector bar

A simple firmware program on the robot processes the speed and steering commands sent from the computer via Bluetooth, and converts them into skid steering motor commands, and sends them to the two drive servo motors.

In surface scanning operations, the SMR is held in place using rubber mounts, which ensures that it is always in contact with the measuring surface. Additionally, the robot has the ability to raise the SMR off the surface on command, if for example, it need to move over a rough surface that may damage the SMR.

An iGPS vector bar and wireless transmitter can also be mounted on top of the robot for iGPS guidance (Figure 5).

2.4. Command and control Software

The command and control software runs on a normal Windows XP personal computer. It consists of instrument interface software and robot control software, as shown in Figure 6. Since the Software Development Kit (SDK) from the instrument vendors often require different programming languages, the separation of the instrument interface and the robot control blocks allows the software to be developed independently from each other.

The communication between the software is facilitated using a Windows API. This modular design also allows the position data sent to the robot control software to be easily switched between different instruments such as the laser tracker or iGPS.

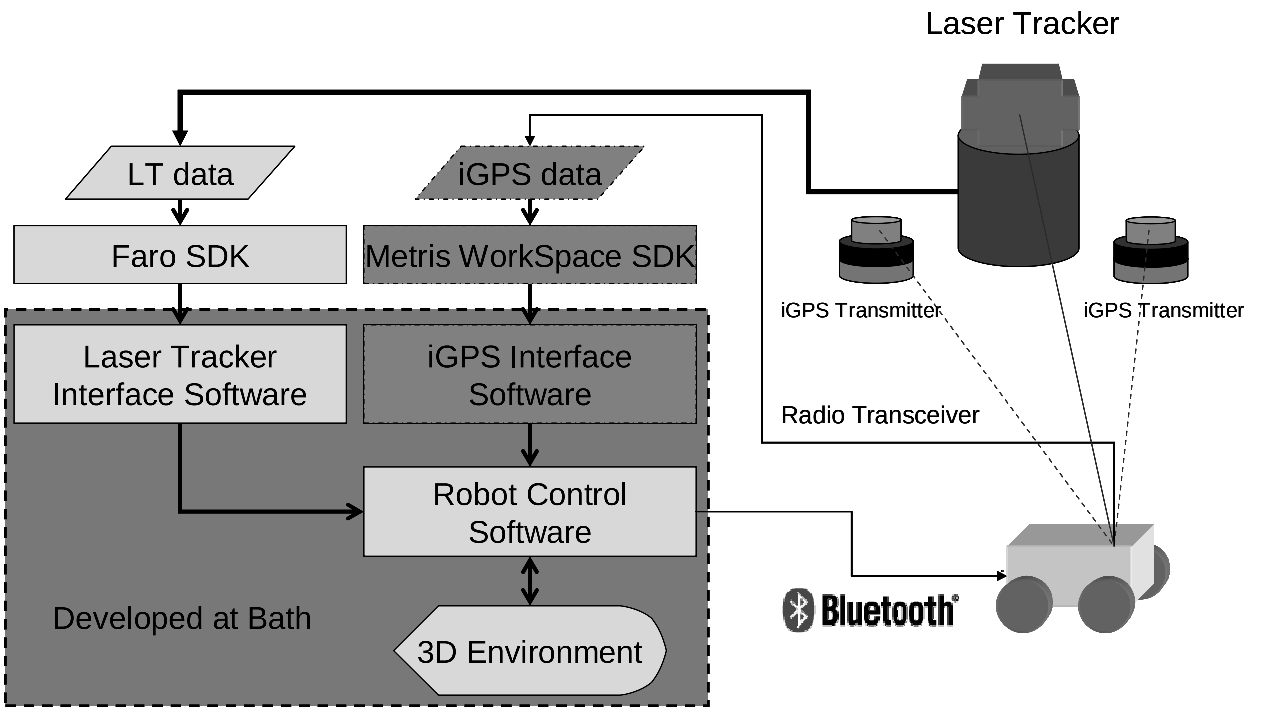

Figure 6 – Software system

2.4.1. Laser tracker and iGPS interface software

The laser tracker interface (Figure 7) is a C# program that sends basic control commands to the laser tracker, and receives position data through an Ethernet TCP/IP connection using the FARO laser tracker SDK.

The software has an option to log the measurement data, and send the real-time data to the robot control software.

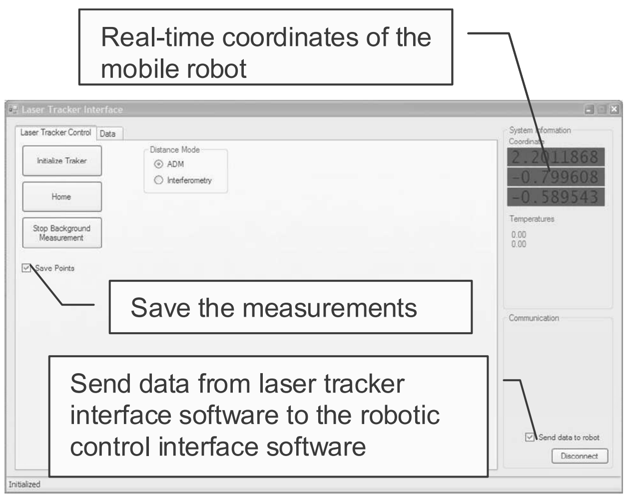

Figure 7 – Laser tracker interface software

The iGPS interface shown in (Figure 8) is very similar to the laser tracker interface, passing the coordinate and orientation data from the Surveyor software to the robot controller, using the iGPS Surveyor™ SDK provided by Metris.

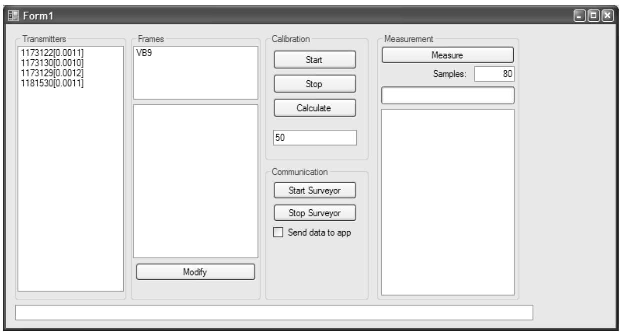

Figure 8 - iGPS interface software

2.4.2. Robot control software

The robot control software (Figure 9) is written in Delphi 7, and communicates with the robot through a Bluetooth serial connection. The software includes a 3D environment showing the relative positions of the robot and the waypoints. The robot waypoints are entered into the waypoint sequencer in plain text format. The software also allows manual remote control of the robot through a PC joystick or gamepad.

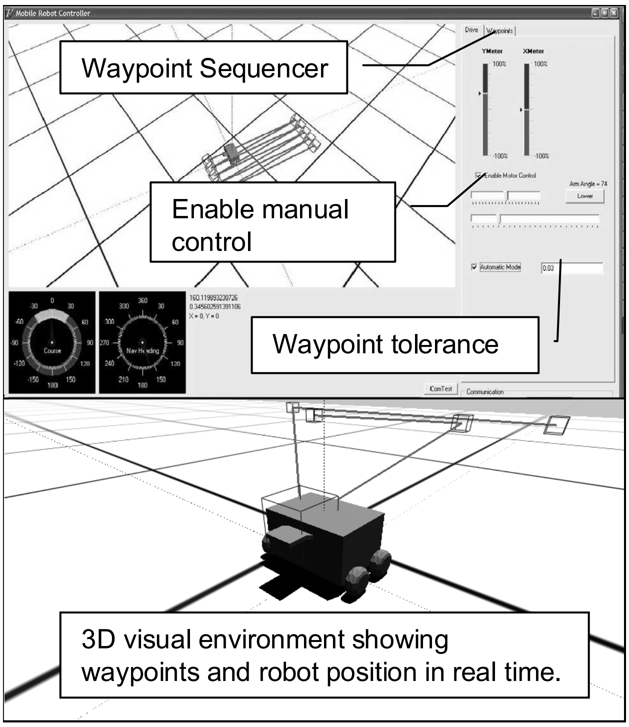

Figure 9 – Robot control software

When in waypoint mode, the robot control software receives the real-time robot position from the laser tracker interface software, generates a correction command and sends the correction to the robot through the Bluetooth link.

To simplify the process of waypoint creation for operations requiring driving in a grid pattern, a MatLab script was written. The script generates a series of waypoints (shown in Figure 9 top) from three manually input coordinates.

2.5. Navigation Method

Since the precise position of the robot is known at all times, the navigation algorithm is exceedingly straightforward. There are only two simple control loops, one for speed and one for course.

The robot speed is in open loop control at a set speed when the robot is more than 40cm from the target waypoint. When the robot is less than 40cm from the target waypoint, speed is decreased linearly, until the robot is within a tolerance distance to the waypoint, at which point speed reduces to zero.

The heading of the robot cannot be measured directly, but its course can be easily calculated from two consecutive positions. In order to reduce measurement noise from the robot vibrations, the minimum distance between the consecutive measurements is set at 5mm. Knowing the course of travel and the course to the target waypoint, a proportional control loop is used to send turning corrections to the robot.

There are a few complications due to the limited angle of view of the SMR. This means that the robot can not turn more than 30 degrees from the laser tracker, or the line of sight to the SMR will be lost. To over come this problem, care needs to be taken when generating the waypoints, such that the robot travels forwards towards the tracker and backwards away from the tracker, rather than turning around 180 degrees.

3. Experiment results

3.1. Robot Repeatability

An experiment was conduced to assess the repeatability of the robot. The robot was commanded to repeatedly travel between two points approximately 1.5m apart 20 times using different waypoint tolerances.

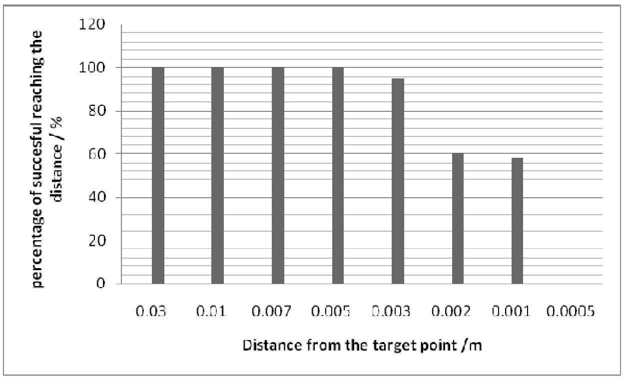

Figure 10 - Robot's probability of reaching the desired waypoint tolerance

(Figure 10) shows that the robot is capable of moving to within tolerance of 5mm or higher from the target point with 100% success. This repeatability value should be put in the context that the range of the Faro laser tracker used in this experiment is 30 metres, thus the robot is capable of reaching any point in the 30m radius circle with a repeatability of 5mm.

The 5mm result is likely to be caused by the course angle measurement distance set for this experiment, as described in the section 2.4. When the waypoint tolerance is less then 5mm, the robot cannot receive any direction updates since it cannot record the next position to compute its course angle. As a result of this, if the robot was turning left when it reaches the distance of 5mm to the target point, it would keep turning left until it travelled more than 5mm. This causes the robot to never reach the waypoint tolerance if it less than 5mm.

However, (Figure 10) also shows that the repeatability is still reasonably good when the desired tolerance is about 1 or 2mm. In these cases, the robot was able to approach the waypoint in a straight line. Therefore no turning correction was needed.

The repeatability is also very much dependent on the robot course angle measurement distance setting. The closer between the records of coordinates when calculating the heading angle, the more accurate the robot could get to the target point.

There are many opportunities for better tuning the control algorithms, since it is rather crude and most gains and constants used in this experiment were chosen somewhat arbitrarily.

3.2. Demonstration of Surface scanning of a wind turbine blade section

The purpose of this experiment is to estimate the shape of a curved surface (a Vestas wind turbine blade section, Figure 11) using the mobile robot as an automated measurement tool, controlled using real-time laser tracker position feedback.

The measurement process involves the robot driving in a zigzag pattern, while carrying the SMR in lower position such that it is in contact with the surface.

These types of scans are typically carried out manually in industry, which is not only time consuming, but also difficult for large parts that the operator cannot easily reach.

Figure 11 - The robot carrying out scanning operation

A MatLab script was used to create the 10 waypoint grid for the robot. The position of the SMR is measured every 1mm the robot travels. The raw data from two trials are plotted in Figure 12.

The robot took slightly different paths in the two trials, especially in the beginning, because the robot starting positions were different.

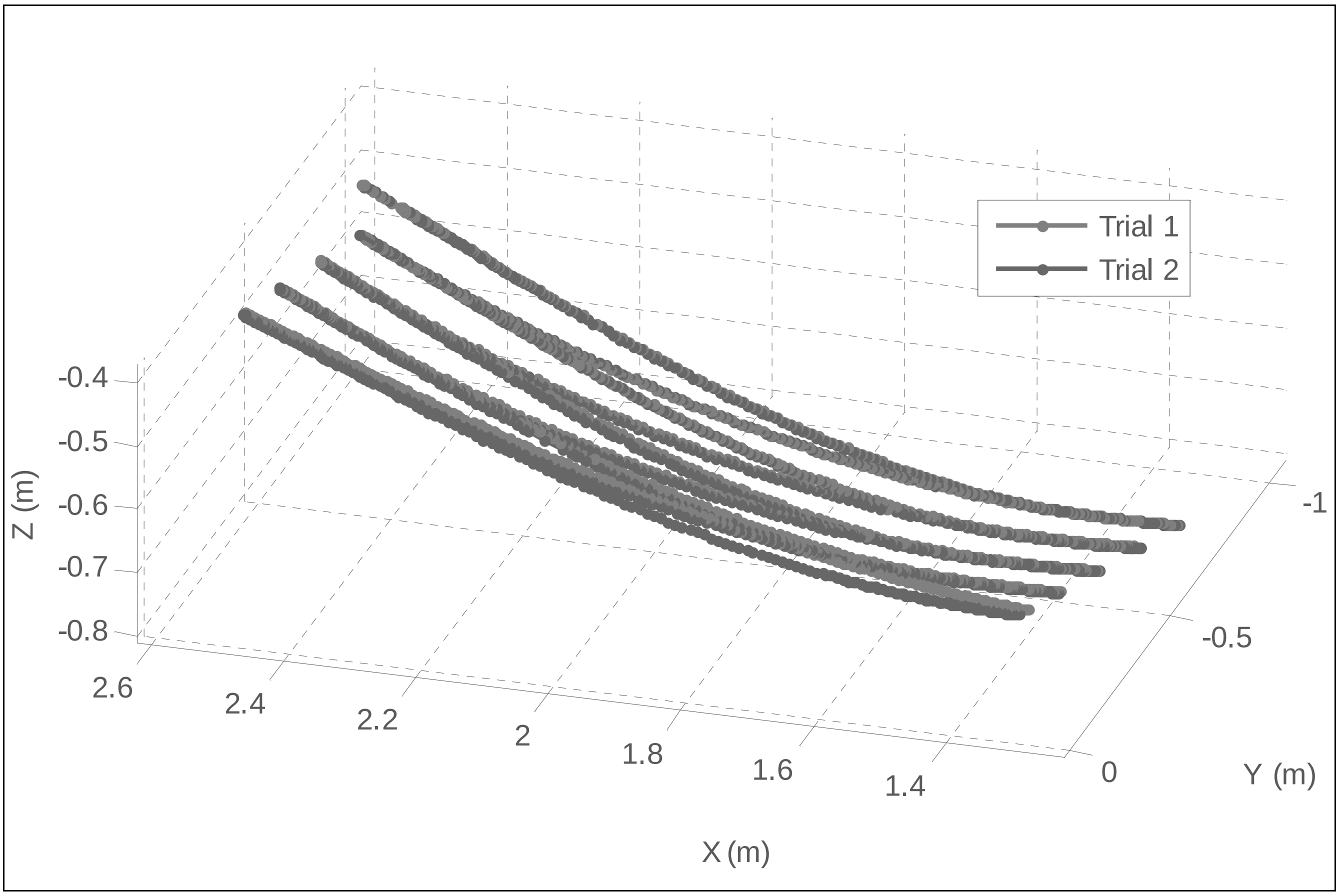

Figure 12 - Scanned data points

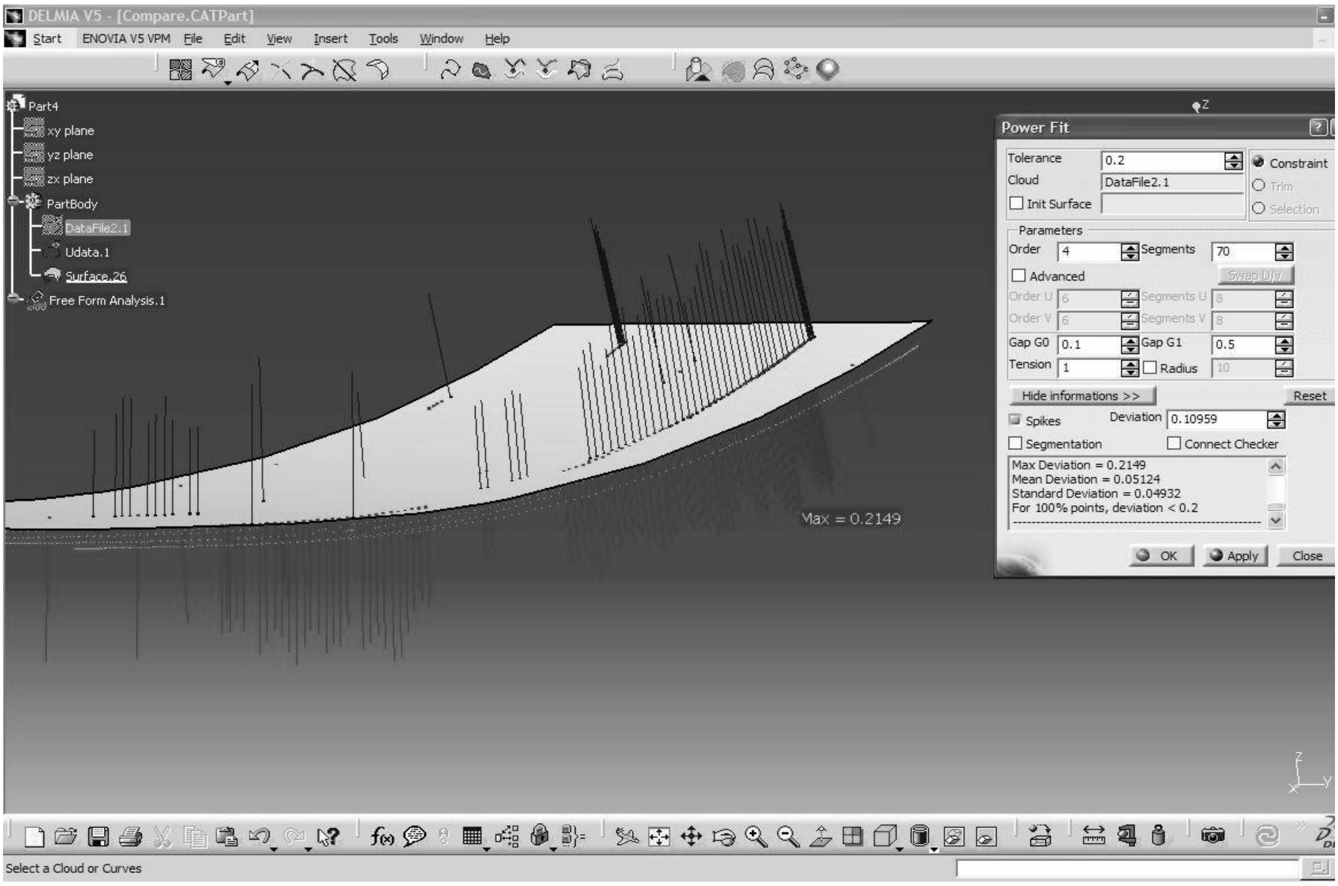

Figure 13 - Best fitting a NURBS surface to the scanned data in CATIA V5

The scanned data can then be imported into a CAD software, such as Catia V5, as shown in Figure 13, in which a surface can be fitted to the data cloud. The fitted surface is then offset in the surface normal direction, by a distance equal to the radius of the SMR, to take into account that the measurement data corresponds to the centre of the SMR, not the surface measured.

Since the data is acquired at laser tracker accuracies (20-30µm), it can be used for operations such as reverse engineering, metrology assisted assembly or quality control.

4. Further work on the iGPS guidance of the KUKA omniMove

The KUKA omniMove platform is a scalable omni-directional vehicle that is designed primarily for material handling, replacing lift trucks, trolleys and over head cranes. The omni-directional drive mechanism allows the vehicle to travel in any direction and orientation. The omniMove platforms come in sizes ranging from less than half a metre long a few kilograms capacity to over tens of meters long and over tens of tons of load capacity.

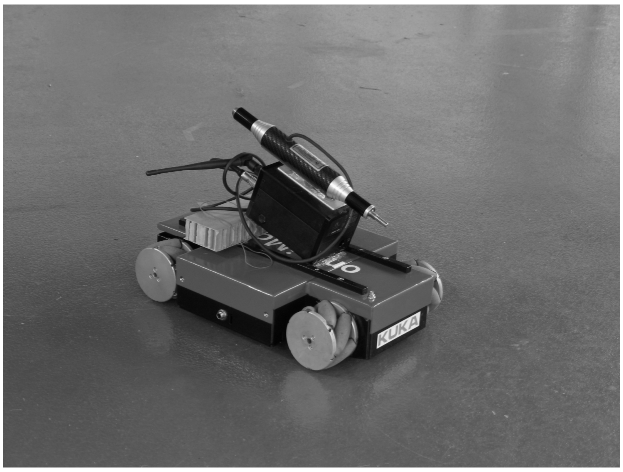

Figure 14 - Mini omniMove carrying an iGPS vector bar

All current omniMove vehicles are driven manually by a trained operator. KUKA Robotics UK is interested in the developing the omniMove into an Automated Guided Vehicle (AGV), to increase production line automation.

Preliminary trials showed that the iGPS is a very suitable system for providing the position and orientation data to drive an omniMove type AGV. Only a small amount of additional work was needed to adapt the Lego robot control software to control an omni-directional vehicle.

Figure 15 – Mini omniMove control station

The working mini omniMove was demonstrated at Airbus ALCAS (Advanced Low Cost Aircraft Structures) open day in 20th-22nd October, 2009. Work is currently being carried out to trial the system on a full size omniMove, in a simulated production environment.

5. Conclusions

In this paper, the possibility of using an external Large Volume Metrology (LVM) instrument such as the laser tracker in mobile robot navigation was investigated. The repeatability of the robot in was experimentally determined to be 5mm, and there exists room for improvement in the robot navigation algorithm.

A surface scanning of a wind turbine blade section was also demonstrated, illustrating possible applications of the method for manufacturing processes.

Metrology guidance simplifies many of the most difficult problems in mobile robot navigation, and the accurate metrology information allows the robot to perform tasks such as measuring the shape of an irregular surface, which would have been very difficult to automate.

A number of improvements can be made in the robot hardware and navigation algorithm. For example, a proper digital filter maybe used to calculate better estimates of the robot course at any given time, rather than the 5mm distance limit used in the experiments described in this paper. Other onboard sensors such as an inertial navigation system may also be used in conjunction with the laser tracker, to improve navigation and achieve 6 DOF measurements.

Given reliability and accuracy of the LVM position data and reduced complexity in integration, the methods described in the paper is currently being applied to develop an industrial AGV prototype.

Acknowledgements

This research has been carried out as part of the IdMRC at the Department of Mechanical Engineering of the University of Bath, under EPSRC Grants No. EP/E002617/1 and EP/E00184X/1. The funding of EPSRC and the support of our industrial partners is gratefully acknowledged.

This paper has been presented in DET2009 conference held at the University of Hong Kong during 14-16 December 2009 and included in the conference proceeding published by Springer.

References

ASME B89.4.19. “Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems”, 2006

Eric Krotkov, Martial Hebert and Reid Simmons, “Stereo Perception and Dead Reckoning for a Prototype Lunar Rover”, Autonomous Robots, 2, 1995, pp 313-331

Estler WT, Edmundson KL, Peggs GN and Parker DH, “Large Scale Metrology-An Update”, CIRP Annals, NIST Technipubs 2002

FARO EUROPE GmbH & Co. KG. “New Faro Laser Tracker SI. 2: Tougher with Exclusive Features” Faro UK technical specification sheet, 2004

ARCSecond. “Indoor GPS technology for Metrology”, White Paper 071502, Dulles, Virginia: ARCSecond 2002

Z. Wang, L. Mastrogiacomo, P. G. Maropoulos, F. Franceschini (2009). Experimental Testing of the Dynamic Tracking Performance of iGPS and Laser Tracker. Laser Metrology and Machine Performance IX, 2009, pp. 305-314.

Guilherme N. Desouza, Avinash C. Kak, “Vision for Mobile Robot Navigation: A Survey”, IEEE Transactions on Pattern Analysis and Machine Intelligence, Volume 24, Issue 2, Feb 2002, pp 237 - 267

Jonathan Dixon and Oliver Henlich, “Mobile Robot Navigation”, Imperial College, 10 June 1997, Retrieved: 11th May, 2009, <http://www.doc.ic.ac.uk/ ~nd/surprise_97/journal/vol4/jmd/>

Kok Seng CHONG and Lindsay KLEEMAN “Accurate Odometry and Error Modelling for a Mobile Robot”, IEEE International Conference on Robotics and Automation, Albuquerque USA, April 1997, pp. 2783-2788.